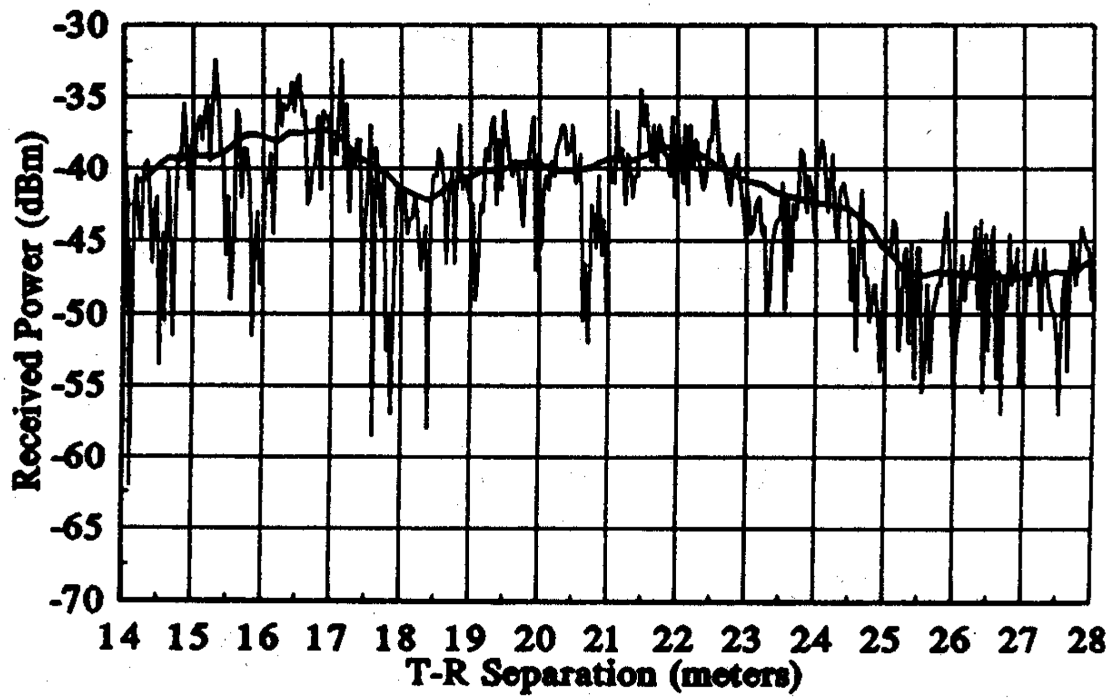
Chapter 3
Mobile Radio Propagation Large-Scale Path Loss

3.1 Introduction to Radio Wave Propagation

- Electromagnetic wave propagation
  - reflection
  - diffraction
  - scattering
- Urban areas
  - No direct line-of-sight
  - high-rise buildings causes severe diffraction loss
  - multipath fading due to different paths of varying lengths
- **Large-scale propagation models** predict the mean signal strength for an arbitrary T-R separation distance.
- **Small-scale (fading) models** characterize the rapid fluctuations of the received signal strength over very short travel distance or short time duration.

- Small-scale fading: rapidly fluctuation
  - sum of many contributions from different directions with different phases
  - random phases cause the sum varying widely. (ex: Rayleigh fading distribution)
- Local average received power is predicted by large-scale model (measurement track of 5λ to 40λ)



3.2 Free Space Propagation Model

- The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear line-of-sight path between them.
  - satellite communication
  - microwave line-of-sight radio link
- Friis free space equation

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

P_t : transmitted power

$P_r(d)$: received power

G_t : transmitter antenna gain

G_r : receiver antenna gain

d : T-R separation distance (m)

L : system loss

λ : wave length in meters

- The gain of the antenna

$$G = \frac{4\pi A_e}{\lambda^2}$$

A_e : effective aperture is related to the physical size of the antenna

- The wave length λ is related to the carrier frequency by

$$\lambda = \frac{c}{f} = \frac{2\pi c}{\omega_c}$$

f : carrier frequency in Hertz

ω_c: carrier frequency in radians

c : speed of light (meters/s)

- The losses L $(L \geq 1)$ are usually due to transmission line attenuation, filter losses, and antenna losses in the communication system. A value of *L=1* indicates no loss in the system hardware.

For the free-space model

$$P_r(d) = K / d^2,$$

$$P_r(d)_{dB} = 10\log(K / d^2) = 10\log(K) - 20\log(d)$$

$P_r(d)_{dB}$ decays with distance as (20 dB/ Decade)

$$P_r(10 d_0)_{dB} - P_r(d_0)_{dB} =$$

$$= 10\log K - 20\log(10 d_0) - [10\log(K) - 20\log(d_0)]$$

$$= 20\log(d_0 / 10 d_0) = -20 dB$$

The received power (free-space model) decreases by 20 dB as distance is increased 10 times

- Isotropic radiator is an ideal antenna which radiates power with unit gain.
- Effective isotropic radiated power (EIRP) is defined as

$$EIRP = P_t G_t$$

and represents the maximum radiated power available from transmitter in the direction of maximum antenna gain as compared to an isotropic radiator.

- Path loss for the free space model with antenna gains

$$PL(dB) = 10\log\frac{P_t}{P_r} = -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right)$$

- When antenna gains are excluded

$$PL(dB) = 10\log\frac{P_t}{P_r} = -10\log\left(\frac{\lambda^2}{(4\pi)^2 d^2}\right)$$

<u>Far-Field (Fraunhofer region)</u>

- The Friis free space model is only a valid predictor for $P_r(d)$ for values of d which is in the far-field (Fraunhofer region) of the transmission antenna.
- The far-field region of a transmitting antenna is defined as the region beyond the far-field distance

$$d_f = \frac{2D^2}{\lambda}$$

where D is the largest physical linear dimension of the antenna.

- To be in the far-filed region the following equations must be satisfied

$$d_f >> D \qquad \text{and} \qquad d_f >> \lambda$$

Free-Space Received Power using Close-in Distances

- The free-space equation does not hold for *d=0*.
- Use close-in distance d_0 that is in the far-field region and is smaller than any distance in the communication system
- The received power at d_0 is known: either measured or calculated at that point using the free-space model

$$P_r(d_0) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L}$$

- The received power $P_r(d)$ at a distance (*d*) may be given by

$$\frac{P_r(d)}{P_r(d_0)} = \left(\frac{d_0}{d}\right)^2 \qquad d \geq d_0 \geq d_f$$

OR

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \qquad d \geq d_0 \geq d_f$$

Free-Space Received Power using Close-in Distances

- Due to the large dynamic range of the received signal power (several orders of magnitude) , it is usually expressed in dB scale as

$$P_r(d)_{dBm} = 10\log\left[P_r(d)\ in\ Milli-Watt\right]$$
$$P_r(d)_{dBW} = 10\log\left[P_r(d)\ in\ Watt\right]$$

- Using this scale the received power for free-space model is

$$P_r(d)_{dB} = P_r(d_0) + 20\log\left(d_0 / d\right) \qquad d \geq d_0 \geq d_f$$

OR

$$P_r(d)\ \text{dBm} = 10\log\left(\frac{P_r(d_0)\ Watt}{0.001\ \text{Watt}}\right) + 20\log\left(\frac{d_0}{d}\right)$$

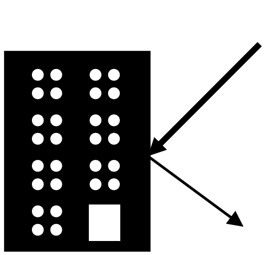
$$P_r(d)\ \text{dBW} = 10\log\left(P_r(d_0)\ Watt\right) + 20\log\left(\frac{d_0}{d}\right)$$

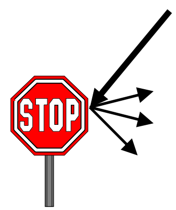
$$d \geq d_0 \geq d_f$$

3.4 The Three Basic Propagation Mechanisms

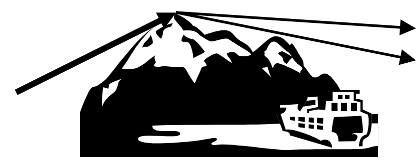
- Basic propagation mechanisms
  - reflection
  - diffraction
  - scattering
- Reflection occurs when a propagating electromagnetic wave impinges upon an object which has very large dimensions when compared to the wavelength, e.g., buildings, walls.
- Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp edges.
- Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength.

- Radio wave propagation is affected by the following mechanisms:
  - reflection at large obstacles
  - scattering at small obstacles
  - diffraction at edges

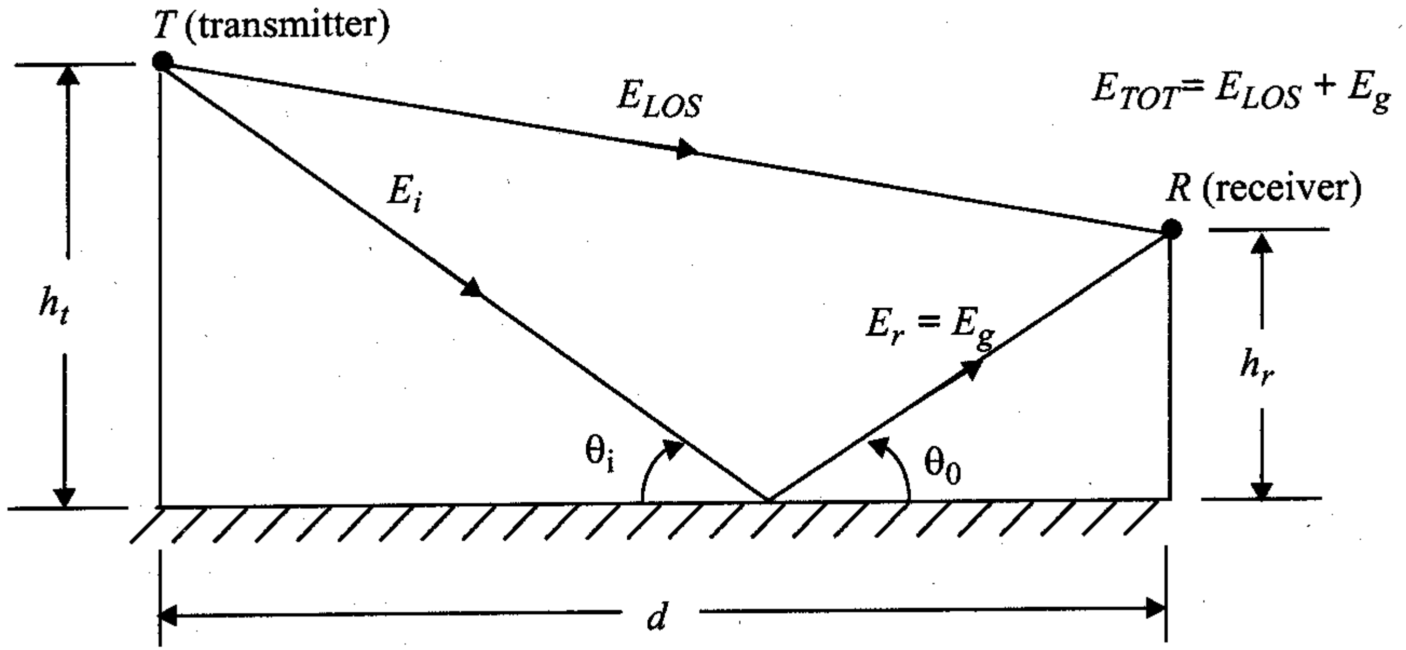

reflection



scattering


diffraction

- Ground Reflection (2-ray) Model



Method of Images

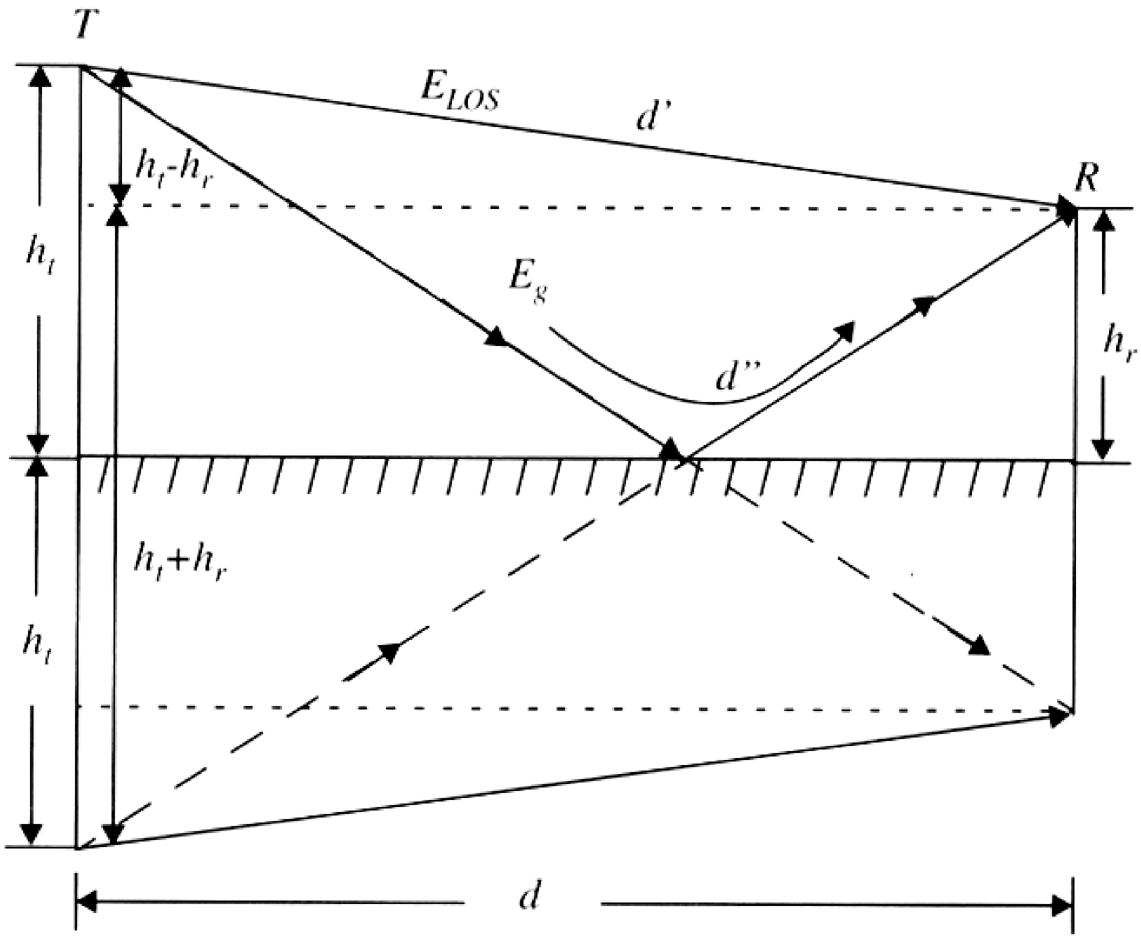
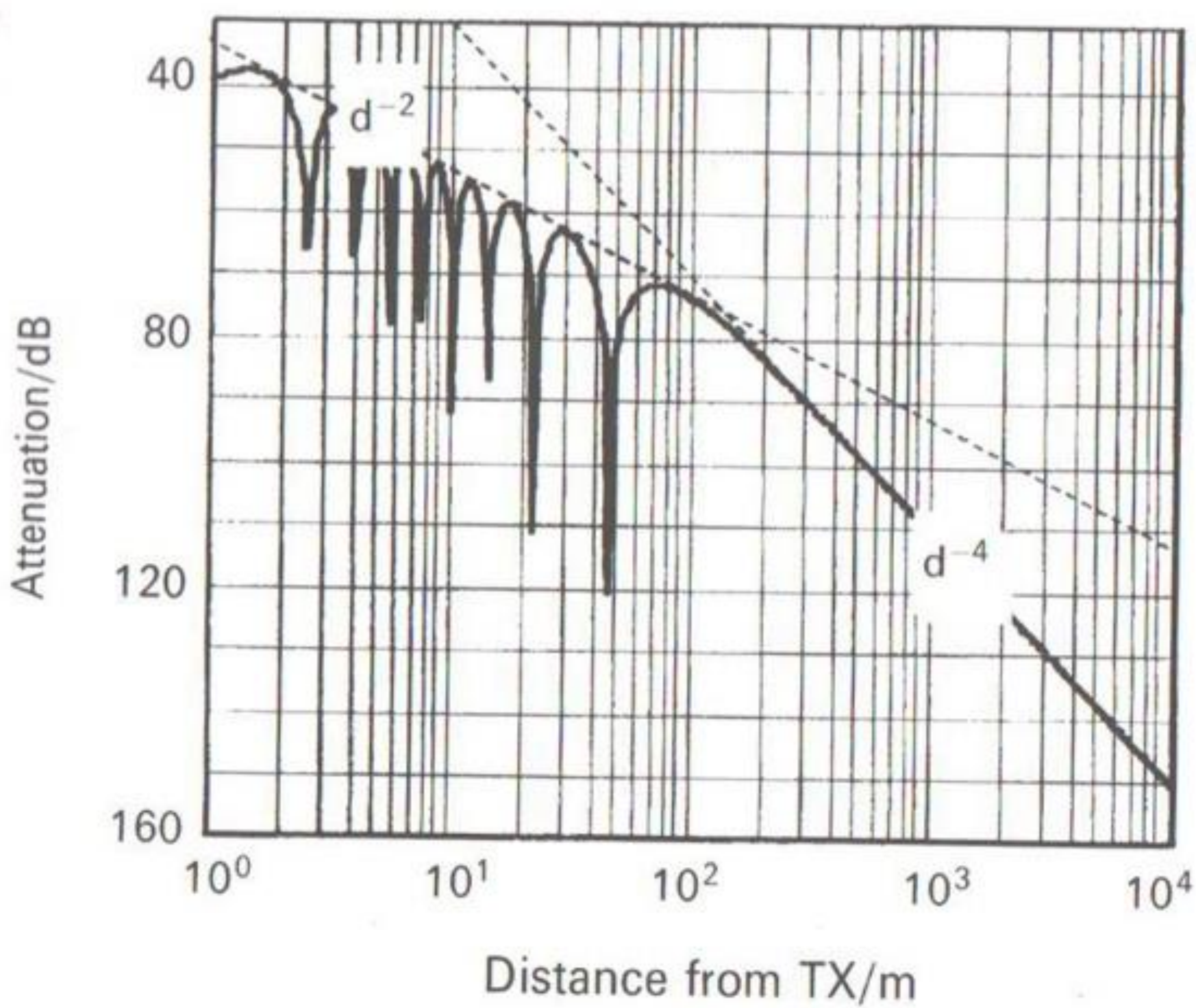


Figure 4.8 The method of images is used to find the path difference between the line-of-sight and the ground reflected paths.



40
80
120
160
Attenuation/dB
d−2
d−4
10^0
10^1
10^2
10^3
10^4
Distance from TX/m

Knife-edge diffraction

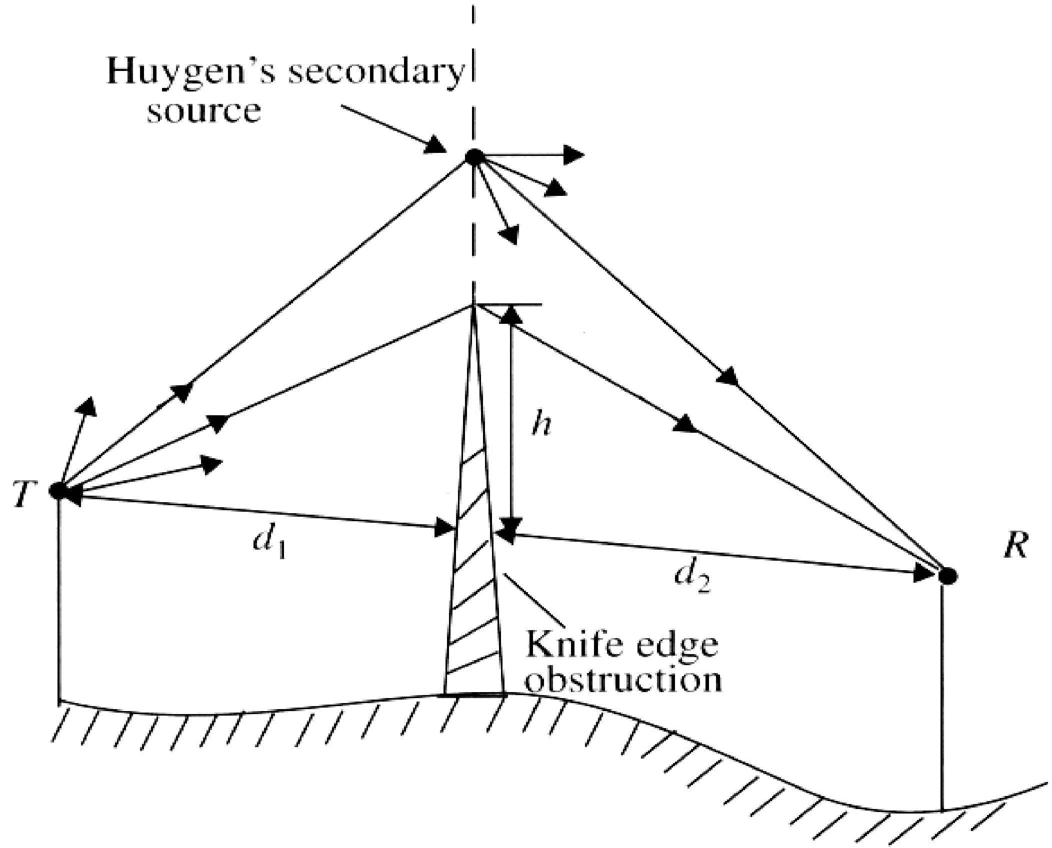
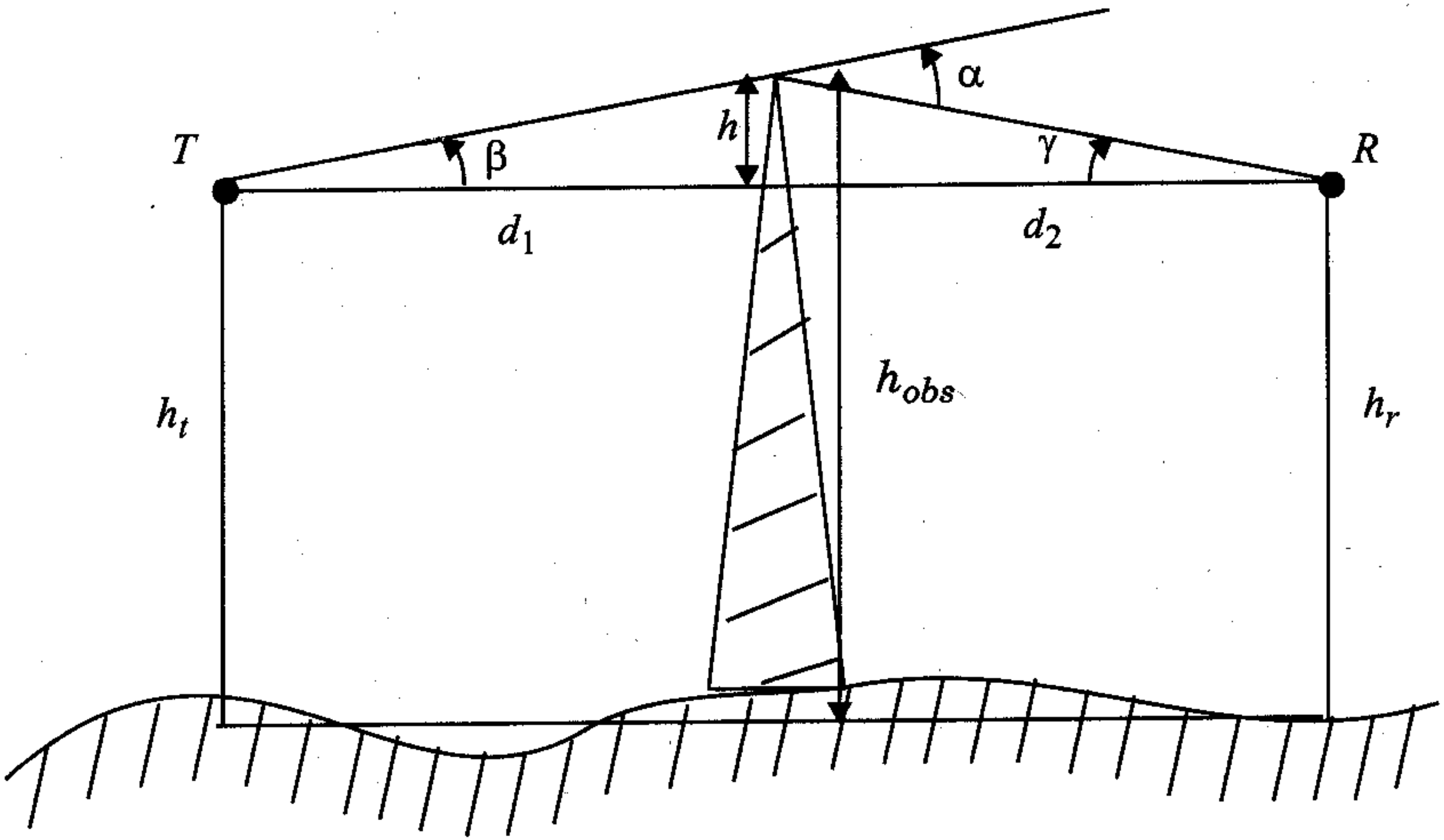
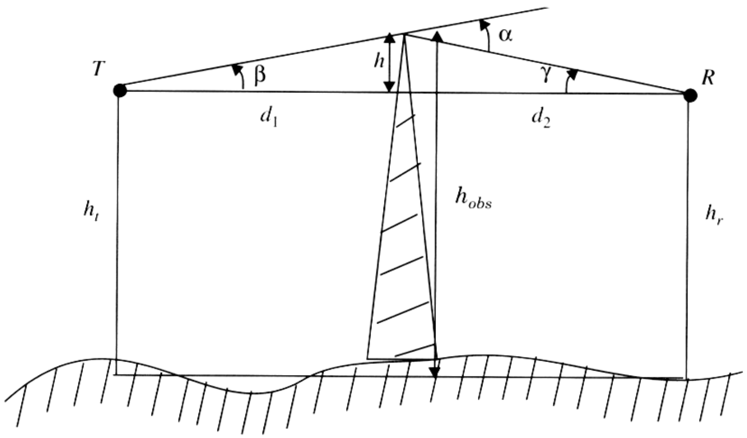


Figure 4.13 Illustration of knife-edge diffraction geometry. The receiver *R* is located in the shadow region.

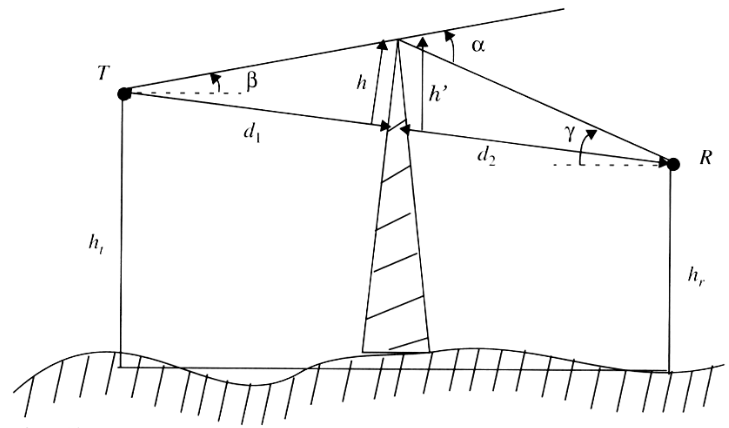
Diffraction



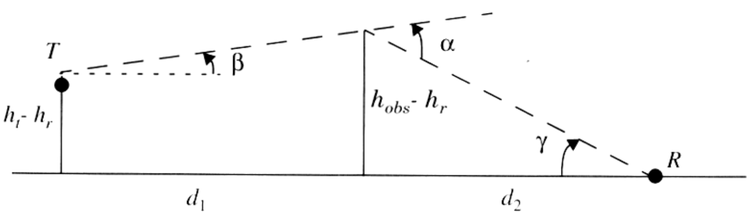
Diffraction geometry



(a) Knife-edge diffraction geometry. The point *T* denotes the transmitter and *R* denotes the receiver, with an infinite knife-edge obstruction blocking the line-of-sight path.



(b) Knife-edge diffraction geometry when the transmitter and receiver are not at the same height. Note that if α and β are small and $h << d_1$ and d_2, then h and h' are virtually identical and the geometry may be redrawn as shown in Figure 4.10c.



(c) Equivalent knife-edge geometry where the smallest height (in this case h_r) is subtracted from all other heights.

Figure 4.10 Diagrams of knife-edge geometry.

Fresnel Screens

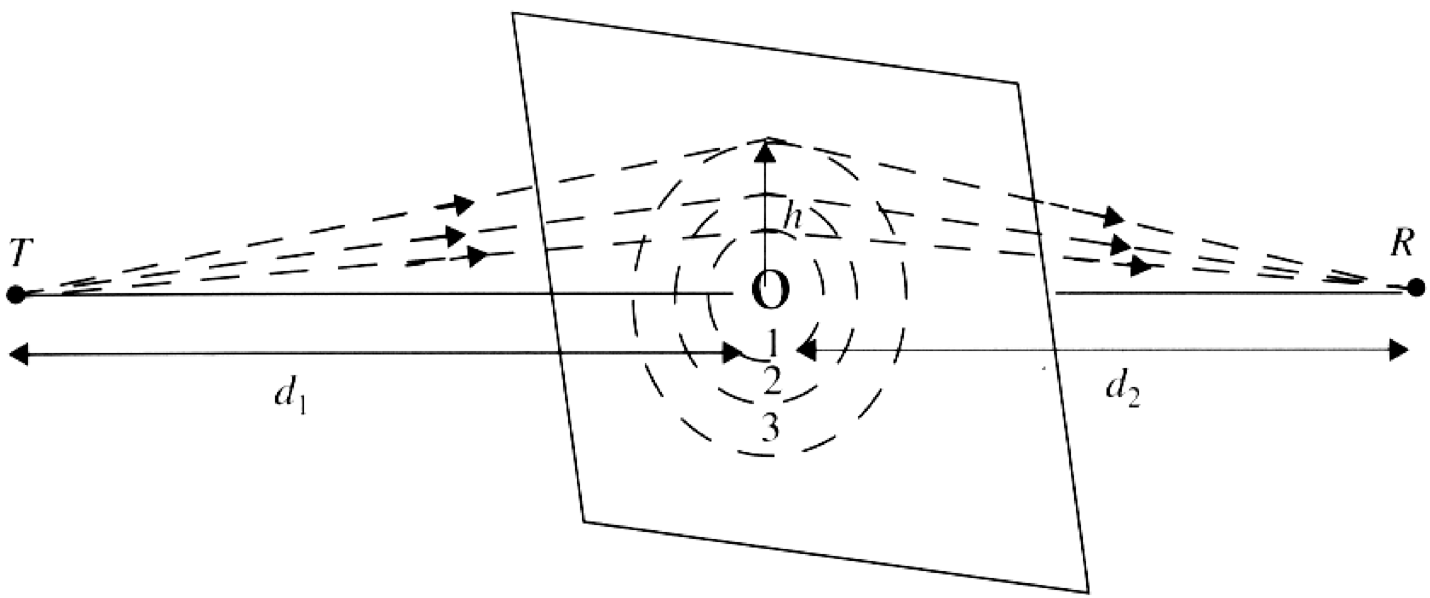
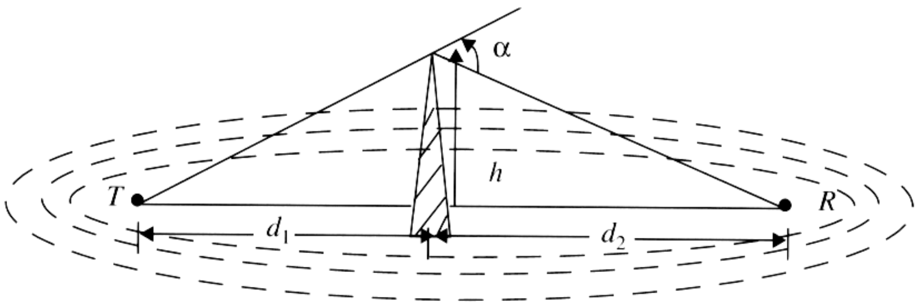
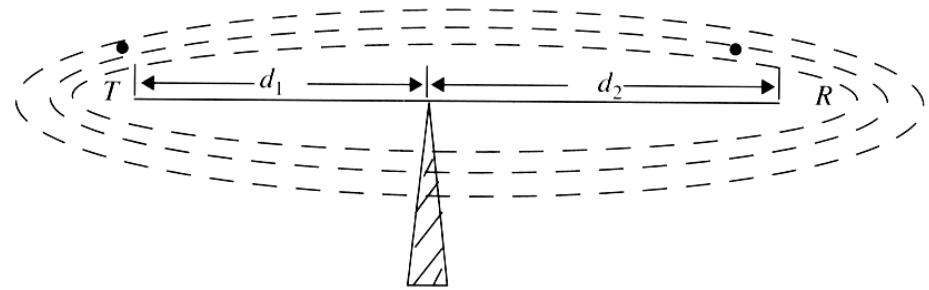


Figure 4.11 Concentric circles which define the boundaries of successive Fresnel zones.

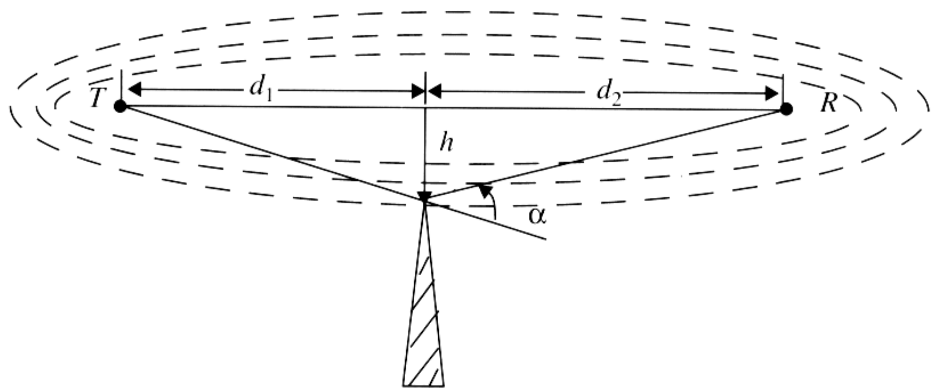
Fresnel diffraction geometry



(a) α and ν are positive, since h is positive

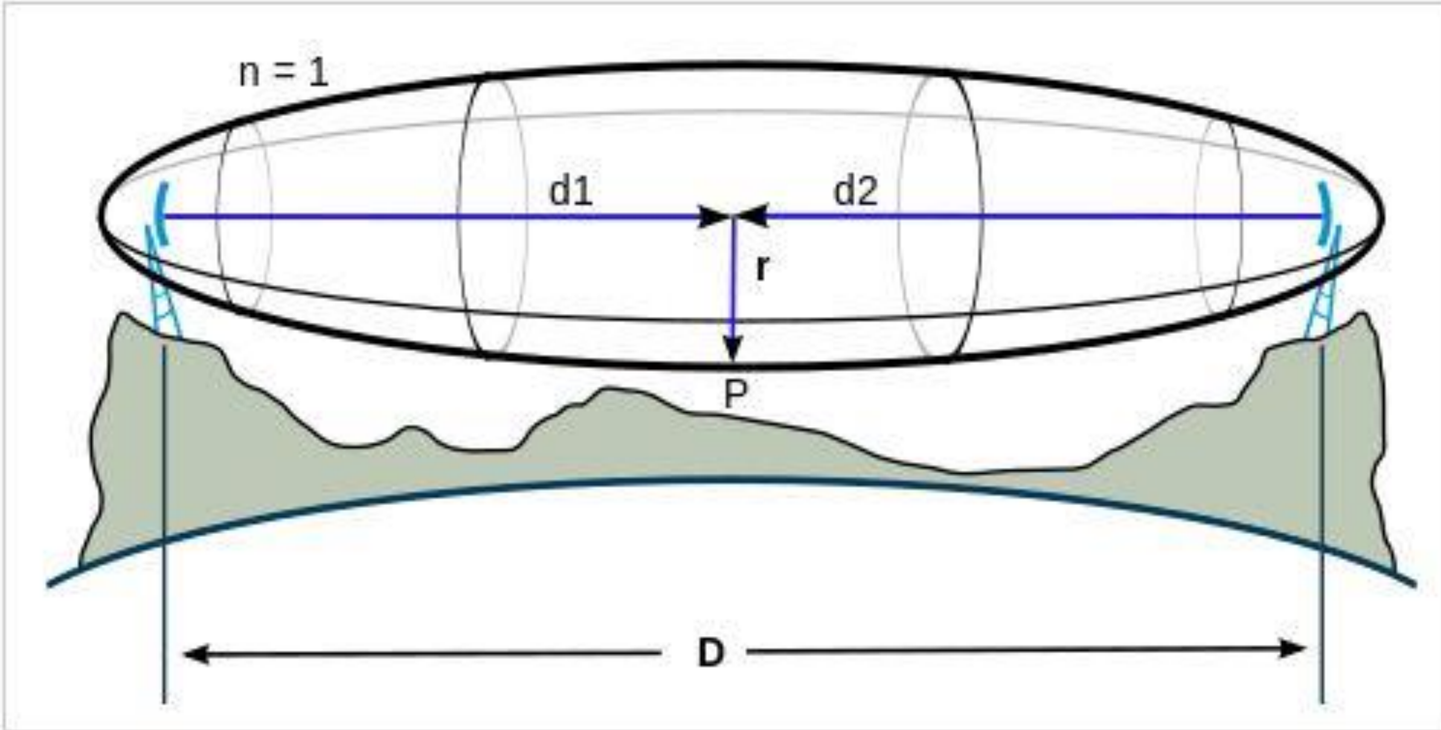


(b) α and ν are equal to zero, since h is equal to zero

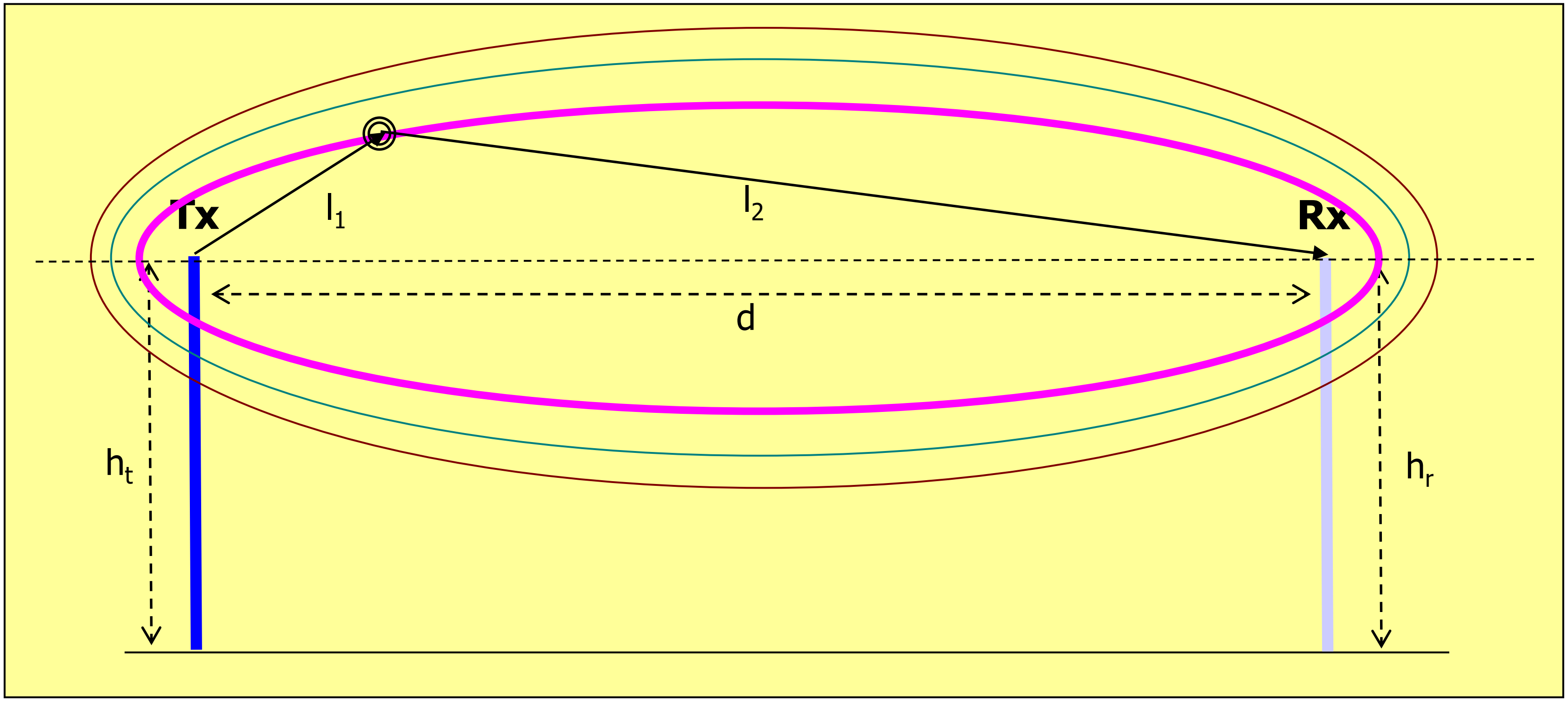


(c) α and ν are negative, since h is negative

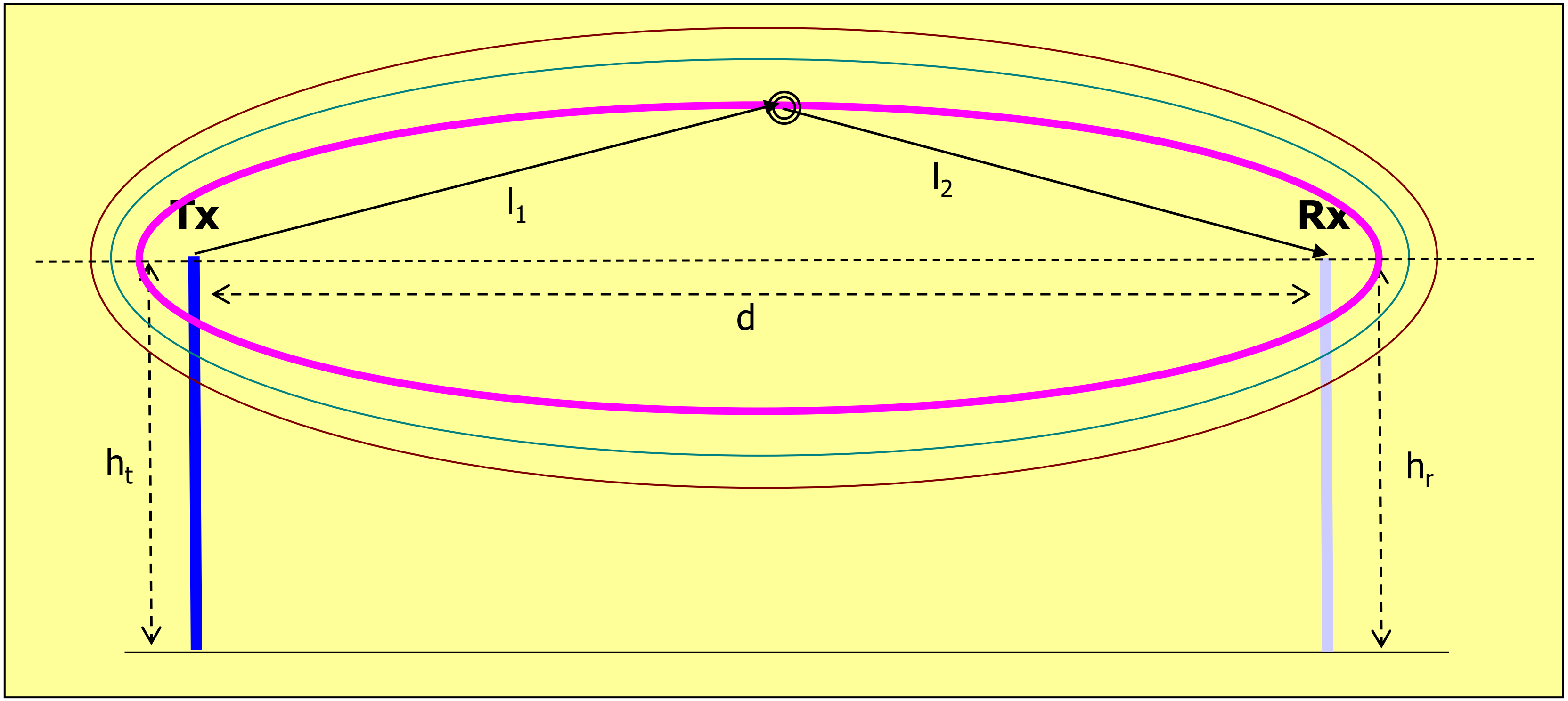
Figure 4.12 Illustration of Fresnel zones for different knife-edge diffraction scenarios.



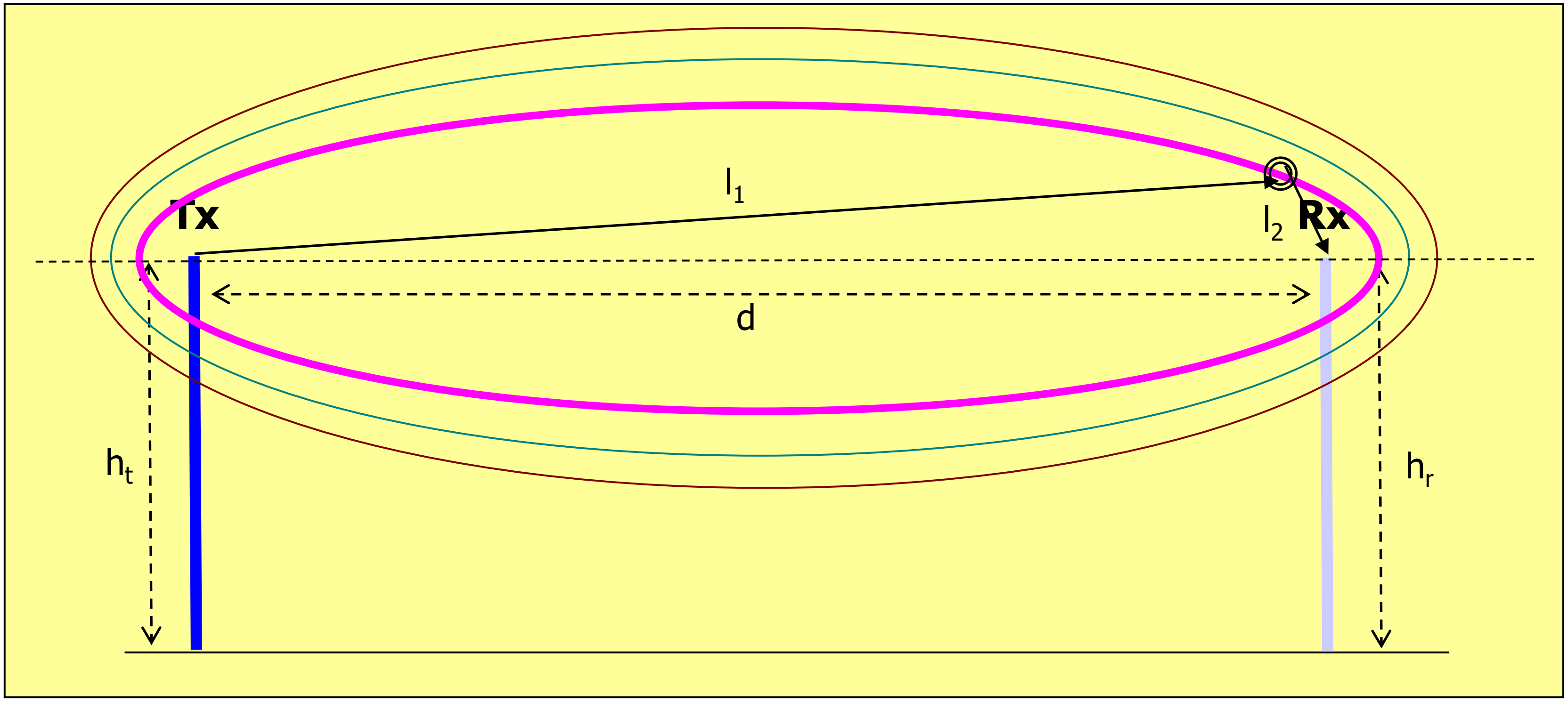
Fresnel zone: *D* is the distance between the transmitter and the receiver; *r* is the radius of the first Fresnel zone (n=1) at point P. P is d1 away from the transmitter, and d2 away from the receiver.



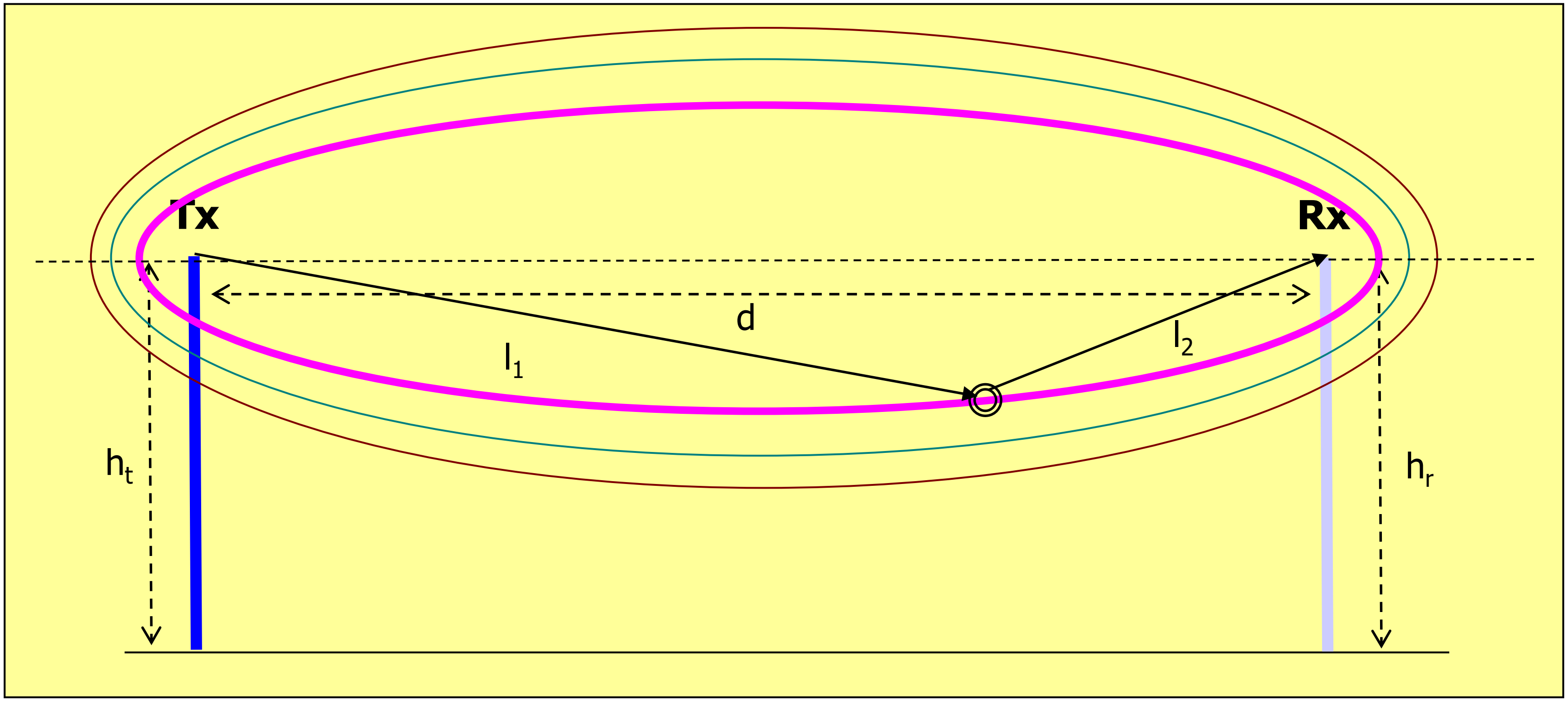
First Fresnel Zone Points ➔ $l_1+l_2-d = (\lambda/2)$



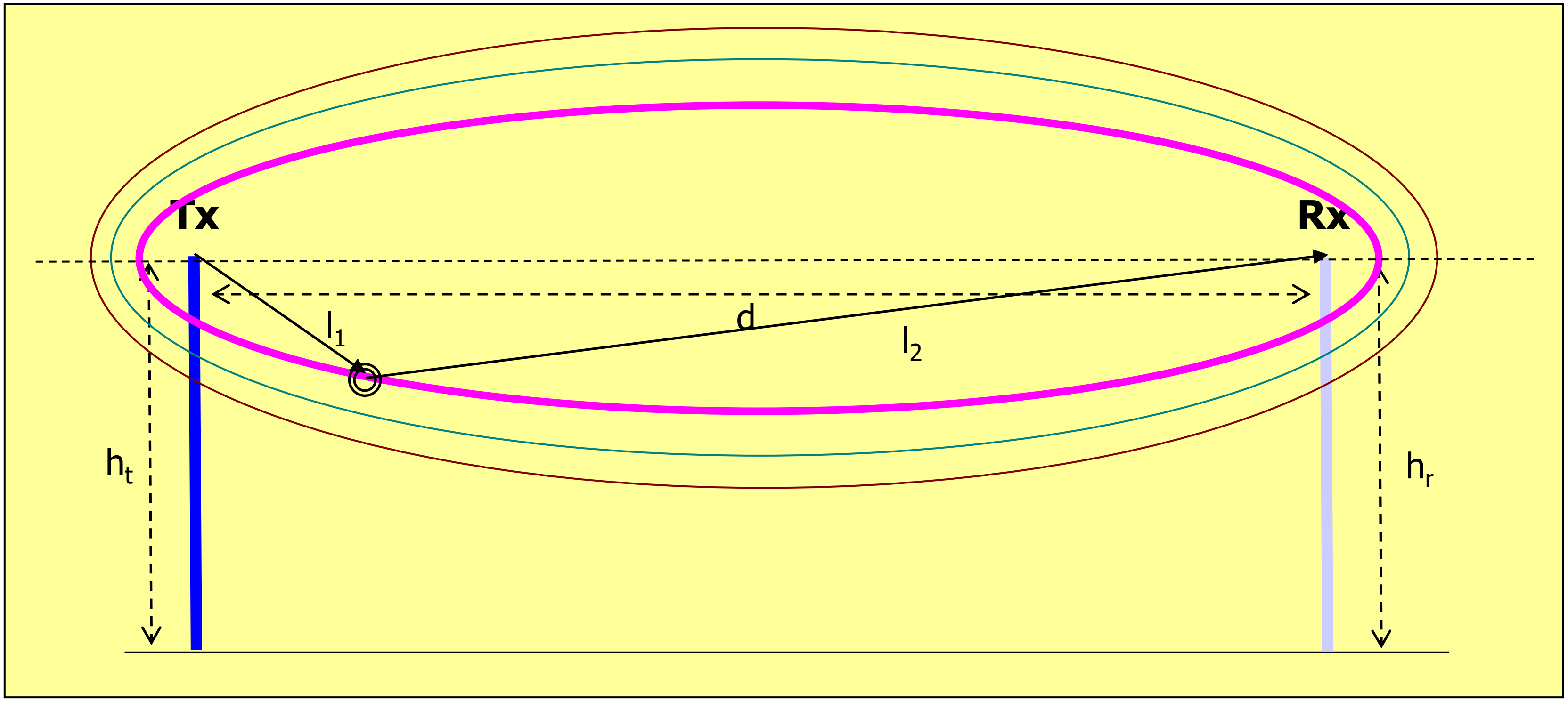
First Fresnel Zone Points ➔ $l_1+l_2-d = (\lambda/2)$



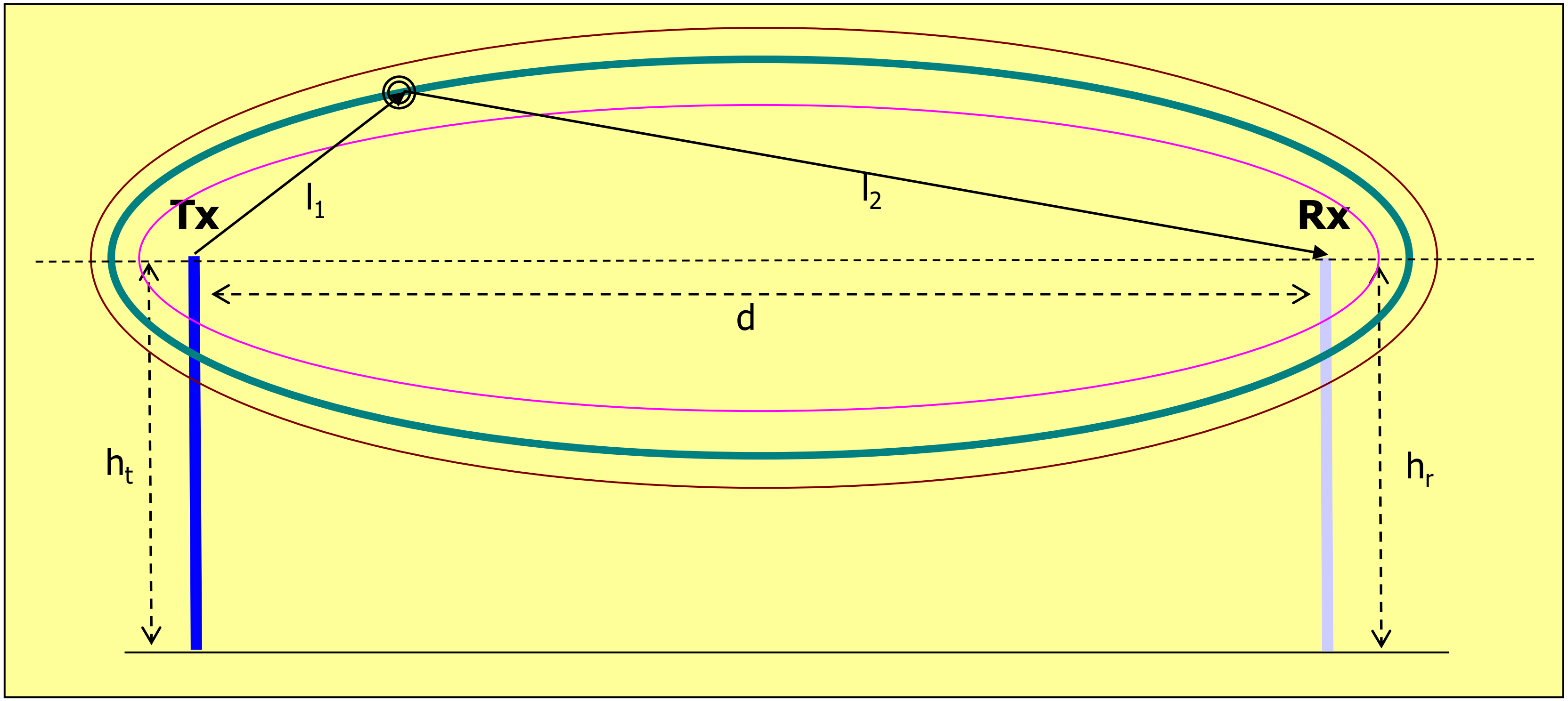
First Fresnel Zone Points ➔ $l_1 + l_2 - d = (\lambda/2)$



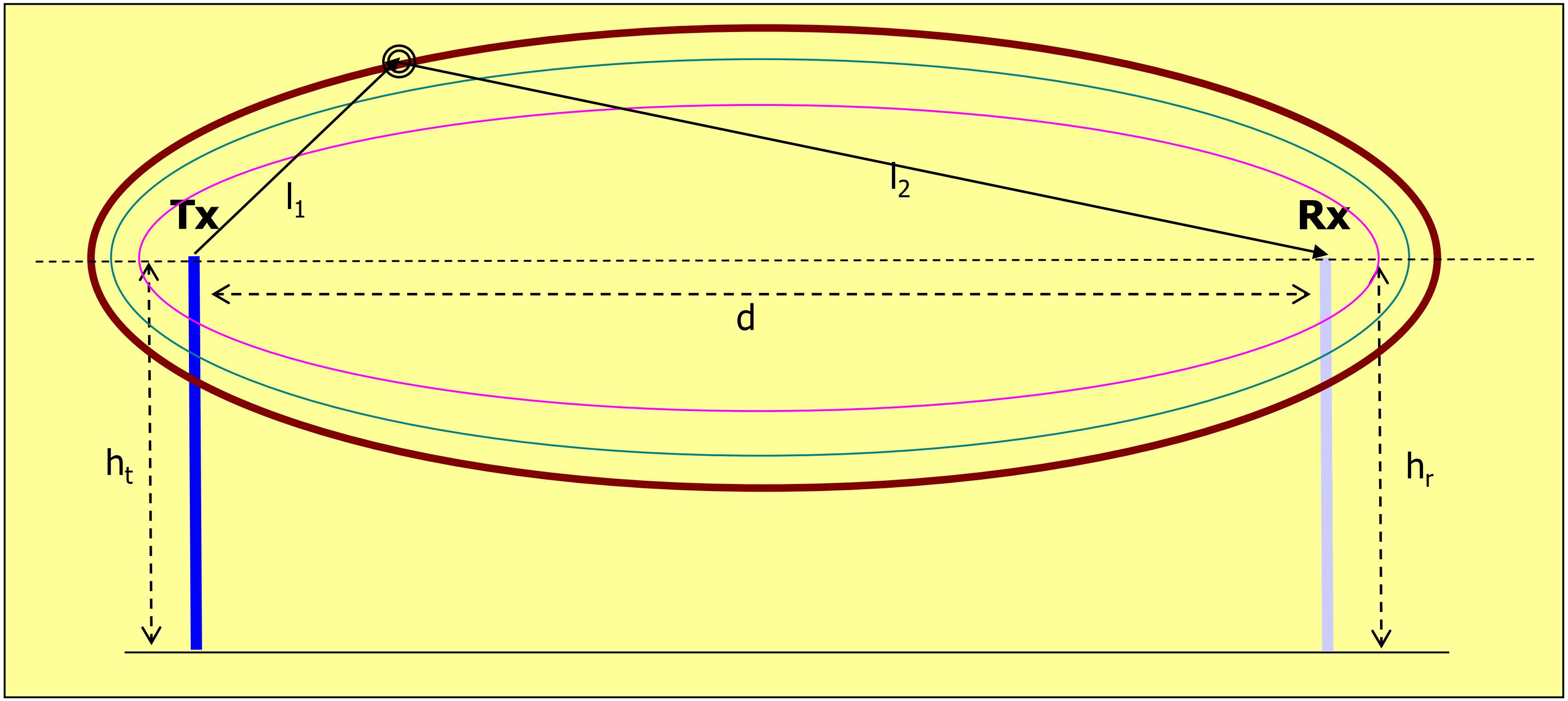
First Fresnel Zone Points ➔ $l_1+l_2-d=(\lambda/2)$



First Fresnel Zone Points ➔ $l_1+l_2-d=(\lambda/2)$



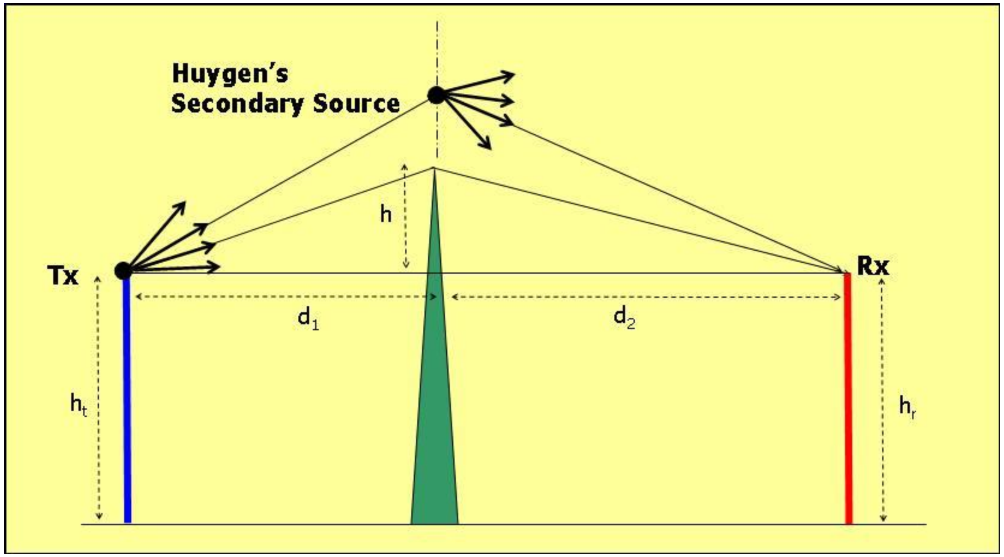
Second Fresnel Zone Points ➔ $l_1+l_2-d = \lambda$



Third Fresnel Zone Points ➔ $l_1+l_2-d = (3\lambda/2)$

Knife-Edge Diffraction Model

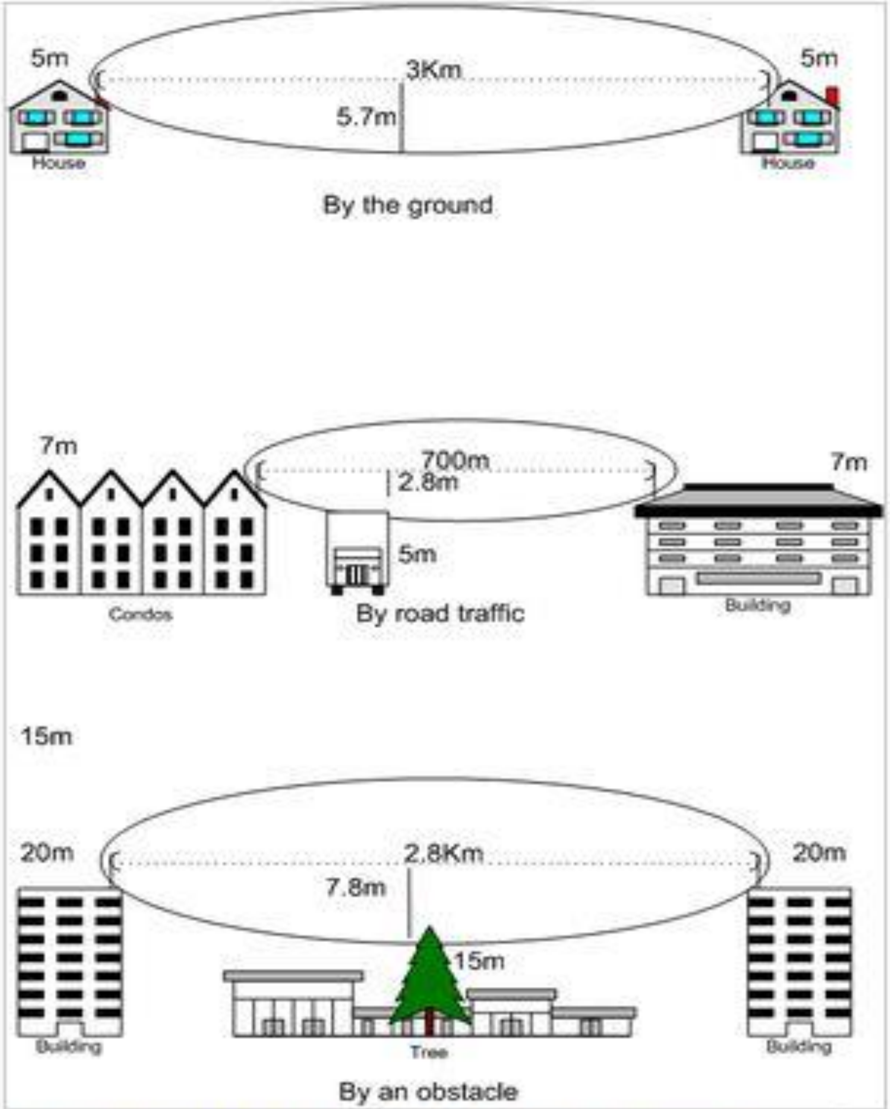
The field strength at point Rx located in the shadowed region is a vector sum of the fields due to all of the secondary Huygen's sources in the plane above the knife-edge



Electric Field Strength, E_d, of a Knife-Edge Diffracted Wave is given By:

$$\frac{E_d}{E_0} = F(v) = \frac{1+j}{2}\int_v^{\infty} \exp\left(-\frac{j\pi t^2}{2}\right)dt$$

E_0: Free-Space Field Strength in absence of Ground Reflection and Knife-Edge Diffraction
F(v) is called the complex Fresnel Integral



Several examples of how the Fresnel zone can be disrupted.

Knife-edge diffraction loss

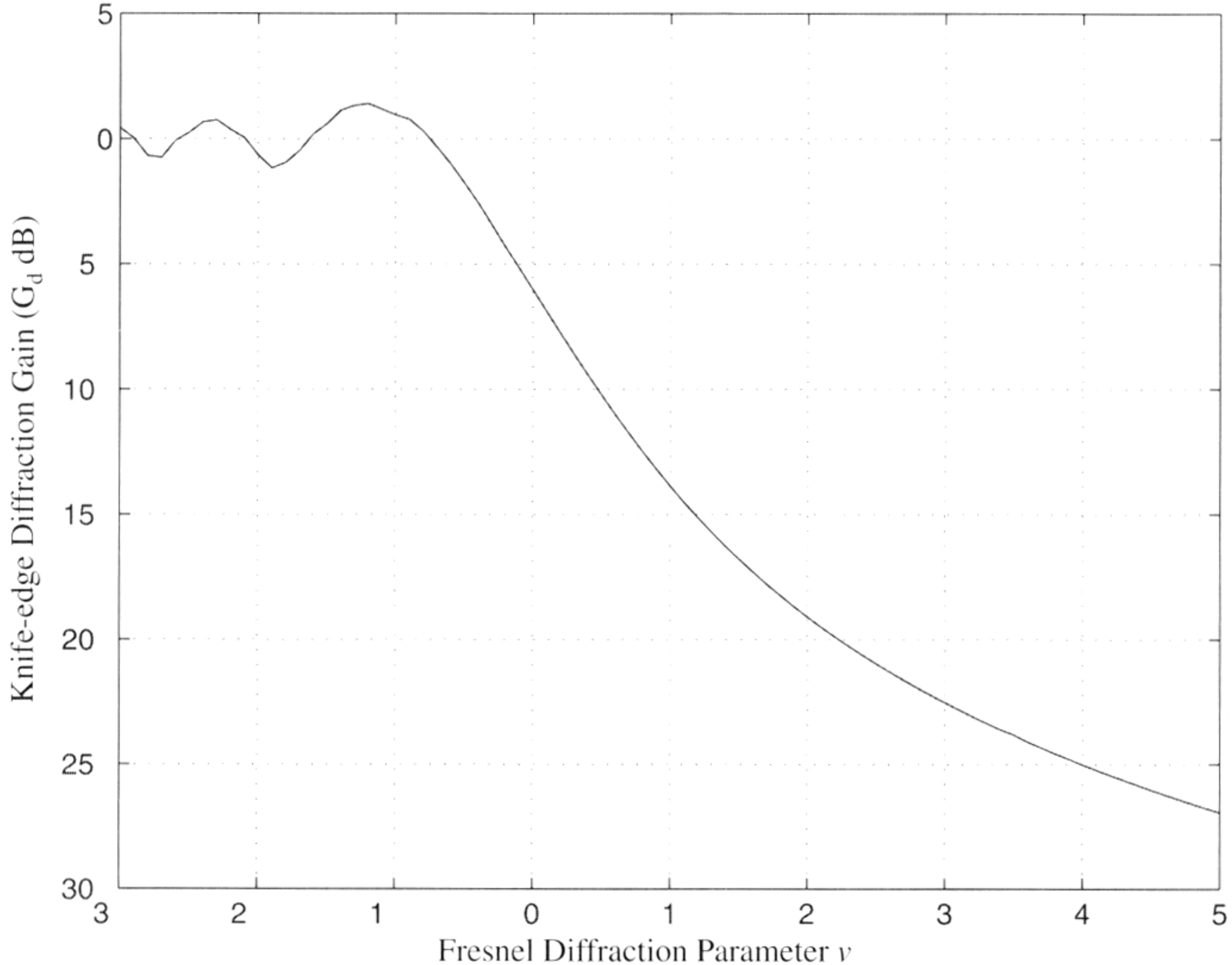


Figure 4.14 Knife-edge diffraction gain as a function of Fresnel diffraction parameter v.

Multiple knife-edge diffraction

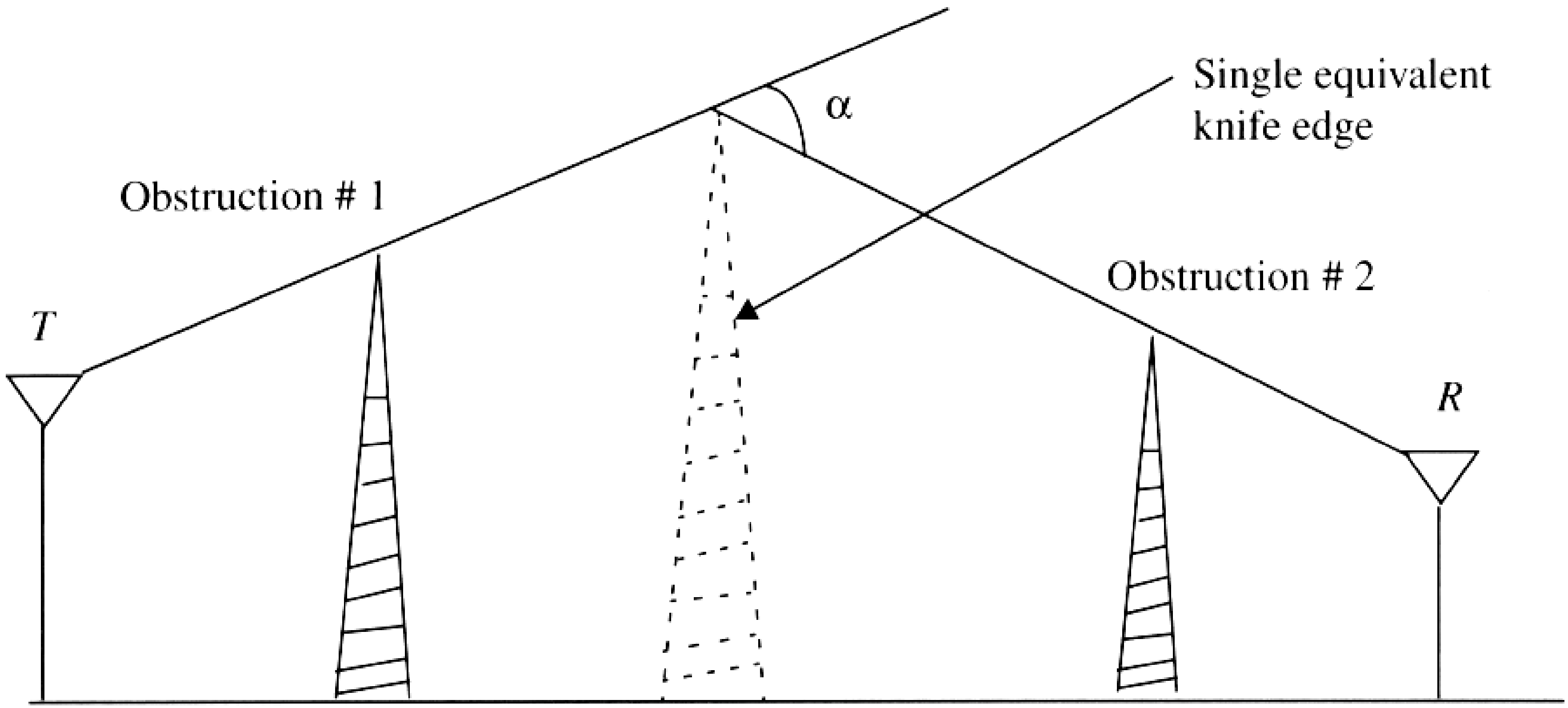


Figure 4.15 Bullington's construction of an equivalent knife edge [from [Bul47] © IEEE].

3.5 Practical Link Budget Design using path Loss Models

- Radio propagation models combine
  - analytical method
  - empirical method
- Log-distance Path Loss Model
  - average received signal power decreases logarithmically with distance
- The average path loss

$$\overline{PL}(d) \propto \left(\frac{d}{d_0}\right)^n$$

or

$$\overline{PL}(d)(dB) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

Table 3.2 Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

- Log-normal Shadowing
  - Surrounding environmental clutter may be different at two different locations having the same T-R separation.
- Measurements have shown that at any value *d*, the path loss *PL(d)* at a particular location is random and distributed normally (normal in dB)

$$PL(d) = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$$

and

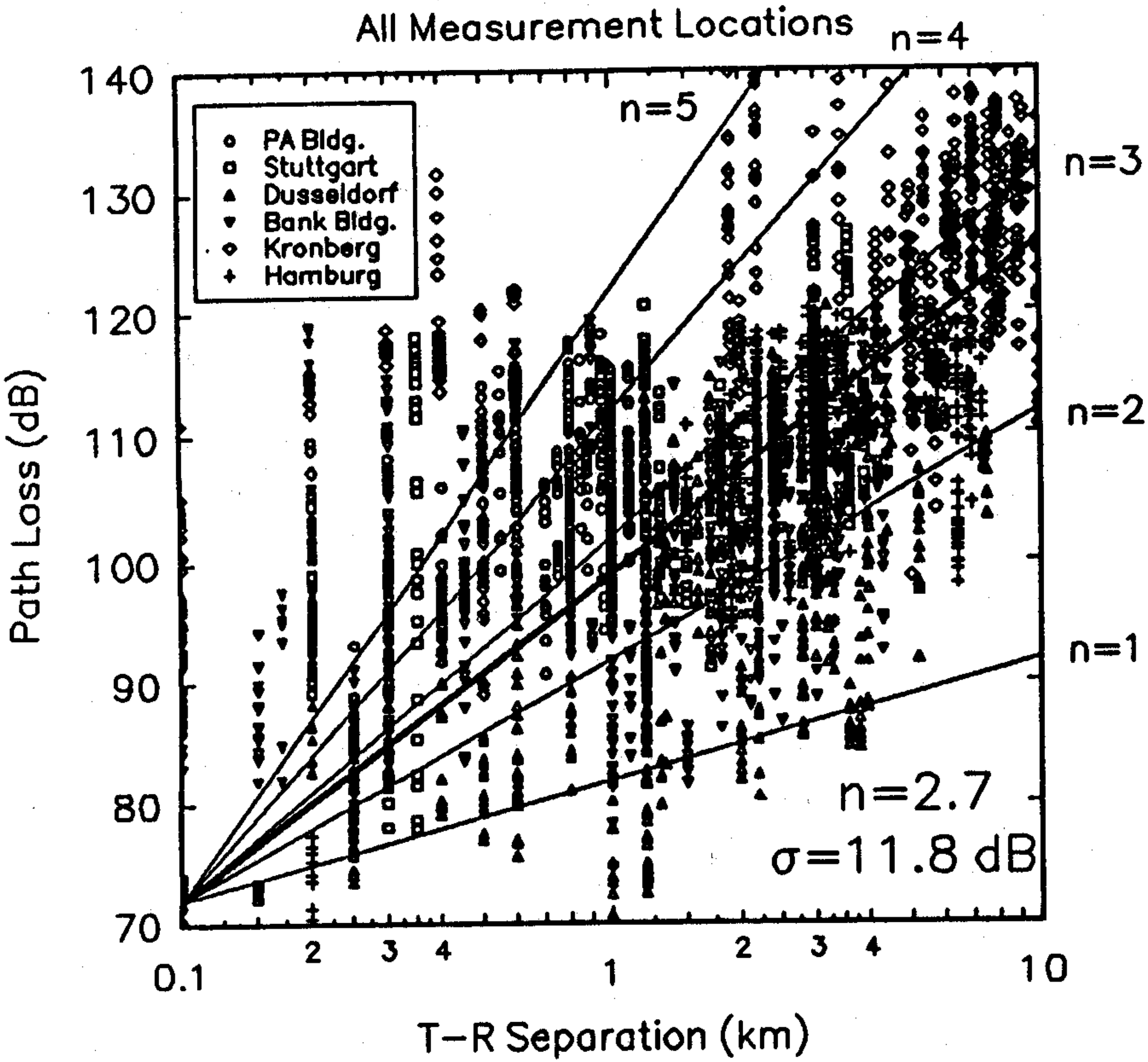
$$P_r(d) = P_t(d) - PL(d)$$

X_σ : zero-mean Gaussian distributed random variable (in dB) with standard deviation σ

- The probability that the received signal level will exceed a certain value γ can be calculated from

$$\Pr[P_r(d) > \gamma] = Q\left(\frac{\gamma - \overline{P_r(d)}}{\sigma}\right)$$

where $\overline{P_r(d)} = P_t(d) - \overline{PL}(d)$



All Measurement Locations
PA Bldg.
Stuttgart
Dusseldorf
Bank Bldg.
Kronberg
Hamburg
n=5
n=4
n=3
n=2
n=1
n=2.7
σ=11.8 dB
Path Loss (dB)
140
130
120
110
100
90
80
70
T–R Separation (km)
0.1
2
3
4
1
2
3
4
10